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RESEARCH MEMORANDUM

EFFECT OF ROTOR LEADING-EDGE SWEEPBACK ON PERFORMANCE OF A TRANSONIC TURBINE

By Warner L. Stewart and Robert Y. Wong

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
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EFFECT OF ROTOR LEADING-EDGE SWEEPBACK ON PERFORMANCE OF A TRANSONIC TURBINE

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SUMMARY

An experimental investigation was conducted to determine the effect of rotor leading-edge sweepback on the aerodynamic performance of a transonic turbine. The sweepback was accomplished through modification of the rotor. Using an unmodified stator with this modified rotor resulted in large incidence angles at the rotor mean and tip sections. A drop in efficiency of only 1 point, from 0.85 for the unmodified unit to 0.84 for the sweptback unit, was obtained. This loss was attributed to the rotor incidence angles and corresponds to the predicted drop in efficiency of approximately $1\frac{1}{2}$ points. Detailed surveys downstream of the turbine rotor at design point indicated that the decreased efficiency occurred in the form of increased losses in the region of the tip section.

INTRODUCTION

High specific weight flows in turbojet engines designed for supersonic flight depend to a great extent upon increased stresses within turbine-rotor blades. Specifically, reference 1 indicates that the rotor hub stress due to centrifugal force becomes the primary constraint in engine designs for operation at flight Mach numbers in excess of 2.0. This constraint occurs as a result of the last-stage turbine-rotor stress determining the exit annulus area and hence limiting the turbine specific weight flow.

It is well known that for a given stress limit an increase in turbine-rotor annulus area can be obtained by means of a blade taper (e.g., ref. 2), but it is also important that this taper be achieved in such a way that a minimum loss in efficiency would be expected.

In general, the throat region and hub section of high-velocity turbines (see ref. 3) are the critical regions from an aerodynamic standpoint. Thus, for a transonic turbine, rotor taper could be achieved by

means of a sweeping back of the less critical rotor leading edge. If the rotor is modified without modification of the stator blades, abnormally high rotor incidence angles occur that might have an adverse effect on turbine performance.

In order to evaluate quantitatively the effect of rotor sweepback on the efficiency of high-velocity turbines, the transonic turbine rotor of reference 3 was accordingly modified and experimentally investigated with the unmodified stator. The results of this investigation are presented herein and include a comparison of the over-all turbine performance of the unmodified (ref. 3) and modified units as well as detailed surveys downstream of the turbine rotor at design point. A comparison of the experimentally obtained loss due to the resultant rotor incidence angles with that theoretically obtained using the incidence loss assumption in reference 4 will also be included.

SYMBOLS

The following symbols are used in this report:

i	incidence angle, deg
$\Delta h'$	specific work output, Btu/lb
N	rotative speed, rpm
p	absolute pressure, lb/sq ft
p_2'	outlet total pressure, sum of static pressure plus pressure corresponding to absolute velocity, lb/sq ft
r	radius
V_{cr}	critical velocity, ft/sec
w	weight flow, lb/sec
γ	ratio of specific heats
δ	ratio of inlet-air total pressure to NACA standard sea-level pressure, p_0'/p^*

ε function of $\gamma, \frac{\gamma^*}{\gamma}\left[\frac{\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma}{\gamma-1}}}{\left(\frac{\gamma^*+1}{2}\right)^{\frac{\gamma^*}{\gamma^*-1}}}\right]$

η_t total adiabatic efficiency, ratio of turbine work based on torque, weight flow, and speed measurements to ideal work based on inlet total temperature and inlet and outlet total pressure

η_l local adiabatic efficiency, total state measurements from surveys downstream of rotor

θ_{cr} squared ratio of critical velocity at turbine inlet to critical velocity at NACA standard sea-level temperature, $(V_{cr,0}/V^*_{cr})^2$

Subscripts:

0 station upstream of stator (all stations shown in fig. 3)

1 station at free-stream between stator and rotor

2 station downstream from turbine

cr conditions at Mach number of 1

t tip

Superscripts:

* NACA standard conditions

' total state

DESCRIPTION OF TURBINE MODIFICATION

The turbine blading used in this investigation was obtained by sweeping back the leading edge of the turbine rotor blades investigated in reference 3. This taper is shown in figure 1 where the unmodified and modified rotor blades are shown projected in the radial-axial plane. In order to maintain the leading-edge radius within limits that were

considered practical, the centers of the new leading-edge circles were placed on the mean camber line of the unmodified blade profile. The suction and pressure surfaces were then faired so that there was no sharp change in curvature. Shown in figure 2 are the unmodified and modified blade profiles at the hub, mean, and tip sections. The coordinates of the modified profiles are given in table I.

The unmodified stator (ref. 3) was used with the modified rotor. Large positive angles of incidence were produced on the order of 13° and 35° at the mean and tip sections, respectively, when the turbine was operated at design point. It is therefore evident that the operation of the modified rotor blades at such high incidence angles will increase the blade losses (fig. 2). These values represent a considerable increase over the 4° used at all sections of the unmodified turbine rotor (see ref. 3). However, a loss in efficiency of only $1\frac{1}{2}$ points was predicted using the loss assumption of reference 4. This assumption is that the velocity component normal to the blade inlet angle represents a total-pressure loss. The small reduction in efficiency as calculated was attributable to the highest incidence angles occurring in the region of lowest velocity. Also, tending to counteract this increased loss is the effect of the reduced mean and tip rotor chord on the profile losses. Thus, from these considerations it is indicated that, theoretically, only small reduction in efficiency is expected as a result of the blade modification.

APPARATUS, INSTRUMENTATION, AND METHODS

The apparatus, instrumentation, and methods of calculating the performance parameters are the same as those described in reference 3. A diagrammatic sketch of the cold-air turbine test setup is shown in figure 3, and a photograph of the modified turbine rotor assembly is shown in figure 4. Test runs were made at constant speeds in even increments of 10 percent of design speed over a range from 30 to 130 percent of design speed. For each speed, the turbine total-pressure ratio was varied from approximately 1.4 to limiting-loading pressure ratio. Turbine inlet temperature and pressure were maintained constant at nominal values of 145° F and 32 inches of mercury absolute, respectively. Detailed radial and circumferential surveys of total pressure and total temperature were made downstream of the rotor (fig. 3, station 2) at approximately design speed and design work output.

RESULTS AND DISCUSSION

A performance map of the swept leading-edge turbine is presented in figure 5(a). The equivalent specific work output $\Delta h'/\theta_{cr}$ is shown as a function of the equivalent-weight-flow - speed parameter $\varepsilon w N/\delta$ with

contours of percentage of design speed, actual total-pressure ratio, and total efficiency superimposed. Rating total-pressure ratio is not used in this figure because the investigation is concerned with the effect of the rotor-blade modification on the turbine aerodynamic losses.

Inspection of figure 5(a) indicates that design point occurs 2 percent below limiting loading and at an efficiency approaching 0.84. Comparison of these results with those obtained for the unmodified turbine can readily be made by using figure 5(b), which is a reprint of the overall performance map presented in reference 3. For the unmodified unit, design point occurred 3 percent below limiting loading and at an efficiency approaching 0.85. Thus, it is indicated that sweeping back the leading edge of the rotor resulted in a 1-point loss in efficiency and an operation slightly closer to limiting loading. The reduction in efficiency is slightly less than the $1\frac{1}{2}$ points predicted as a result of the high rotor incidence angles. The difference might be attributed to the effect of the reduced mean and tip chords on the profile loss. However, little significance is attached to the difference, as it is on the order of the accuracy of the turbine efficiency. It might also be mentioned that the change in turbine exit flow angle was sufficiently small that the rating efficiency was also reduced by 1 point (0.84 to 0.83).

Figure 5 also indicates that the modified turbine had a peak efficiency of slightly over 0.86 which is approximately 1 point greater than that of the unmodified turbine (0.85). This improvement in peak efficiency can probably be attributed to the shift in the region of zero average incidence angle from design speed to speeds above design where the peak efficiency region occurs.

In order to study the performance of the turbine rotor at design point, detailed circumferential and radial surveys were taken downstream of the rotor and converted into local efficiencies. The peak local efficiency was then selected from circumferential surveys at a given radius as most representative of the rotor performance and is presented in figure 6. These peak values of local efficiency are considered to be most representative of rotor performance because they represent flow along streamlines which emanate from the regions of flow between the stator-blade wakes. Also included for comparative purposes is the curve obtained for the unmodified turbine. (This curve is taken from fig. 8 of ref. 5 and extended with known data to the wall region.) Over the lower two-thirds of the annulus (radius ratio from 0.7 to 0.9), the efficiency curves are approximately the same. In the region of the tip, however, the efficiency of the swept leading-edge turbine drops off from that of the unmodified unit. This condition might be expected as the low momentum fluids occurring as a result of the rotor incidence losses would tend to be forced out to the tip by centrifugal force showing up at the turbine exit as the tip loss.

CONCLUDING REMARKS

The results of this investigation indicate that for the particular turbine investigated, only a small reduction in efficiency was obtained as a result of the sweepback taper. It must be pointed out, however, that the unmodified turbine unit had a moderate efficiency of 0.85 and that the loading of the rotor was not too great. Thus, the effect of the swept leading edge on the performance of a more efficient or more highly loaded turbine is still unknown. It might also be pointed out that if the stator had been modified also so that no incidence loss would have been incurred at design point, the modified turbine may very well have had an efficiency at least equal to that of the unmodified turbine. Thus, the results indicate that this form of rotor-blade taper may offer a potential of rotor-hub stress reduction without serious penalty in efficiency.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, March 7, 1955

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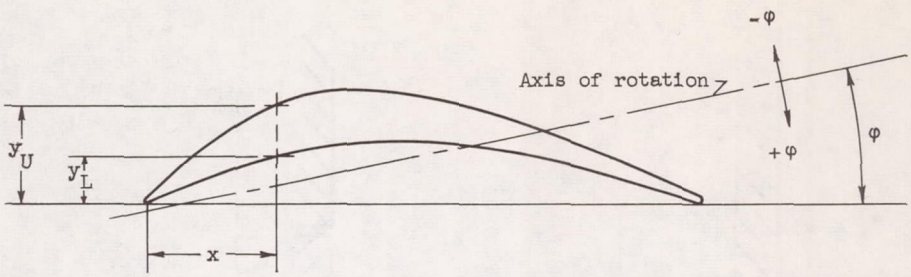
2. LaValle, Vincent L., and Huppert, Merle C.: Effects of Several Design Variables on Turbine-Wheel Weight. NACA TN 1814, 1949.

3. Stewart, Warner L., Wong, Robert Y., and Evans, David G.: Design and Experimental Investigation of Transonic Turbine with Slight Negative Reaction Across Rotor Hub. NACA RM E53L29a, 1954.

4. Stewart, Warner L., and Evans, David G.: Analytical Study of Losses at Off-Design Conditions for a Fixed-Geometry Turbine. NACA RM E53K06, 1954.

5. Wong, Robert Y., Monroe, Daniel E., and Wintucky, William T.: Investigation of Effect of Increased Diffusion of Rotor-Blade Suction-Surface Velocity on Performance of Transonic Turbine. NACA RM E54F03, 1954.

TABLE I. - MODIFIED ROTOR-BLADE COORDINATES



x, in.	Hub		Mean		Tip	
	Leading-edge radii, in.					
	0.015		0.30		0.045	
	Trailing-edge radii, in.					
	0.020		0.020		0.020	
	φ, deg					
	-7.3		15.4		30.8	
	Radius ratio, r/r_t					
	0.70		0.85		1.00	
	y_U,in.	y_L,in.	y_U,in.	y_L,in.	y_U,in.	y_L,in.
0	0.015	0.015	0.030	0.030	0.045	0.045
.100	.138	.066	.210	.032	.130	.011
.200	.254	.142	.322	.076	.179	.028
.300	.362	.211	.404	.116	.219	.044
.400	.458	.272	.467	.156	.253	.058
.500	.540	.326	.510	.192	.277	.070
.600	.610	.373	.539	.222	.293	.083
.700	.670	.414	.563	.249	.302	.092
.800	.721	.450	.577	.271	.307	.100
.900	.764	.481	.587	.290	.305	.104
1.000	.800	.508	.589	.305	.301	.109
1.100	.829	.531	.587	.314	.295	.112
1.200	.851	.550	.576	.320	.286	.116
1.300	.866	.564	.562	.320	.275	.116
1.400	.874	.574	.544	.319	.260	.114
1.500	.876	.580	.521	.314	.241	.109
1.600	.872	.581	.494	.306	.223	.105
1.700	.862	.578	.465	.294	.200	.098
1.800	.846	.570	.431	.280	.179	.091
1.900	.824	.557	.394	.259	.158	.081
2.000	.796	.539	.355	.238	.135	.071
2.100	.761	.516	.311	.213	.113	.056
2.200	.718	.487	.264	.181	.091	.040
2.300	.667	.453	.221	.151	.069	.022
2.400	.607	.413	.174	.113	.047	.003
2.442	----	----	----	----	.020	.020
2.500	.538	.367	.128	.073		
2.600	.459	.315	.080	.032		
2.698	----	----	.020	.020		
2.700	.371	.256				
2.800	.278	.189				
2.900	.182	.113				
3.000	.086	.028				
3.056	.020	.020				

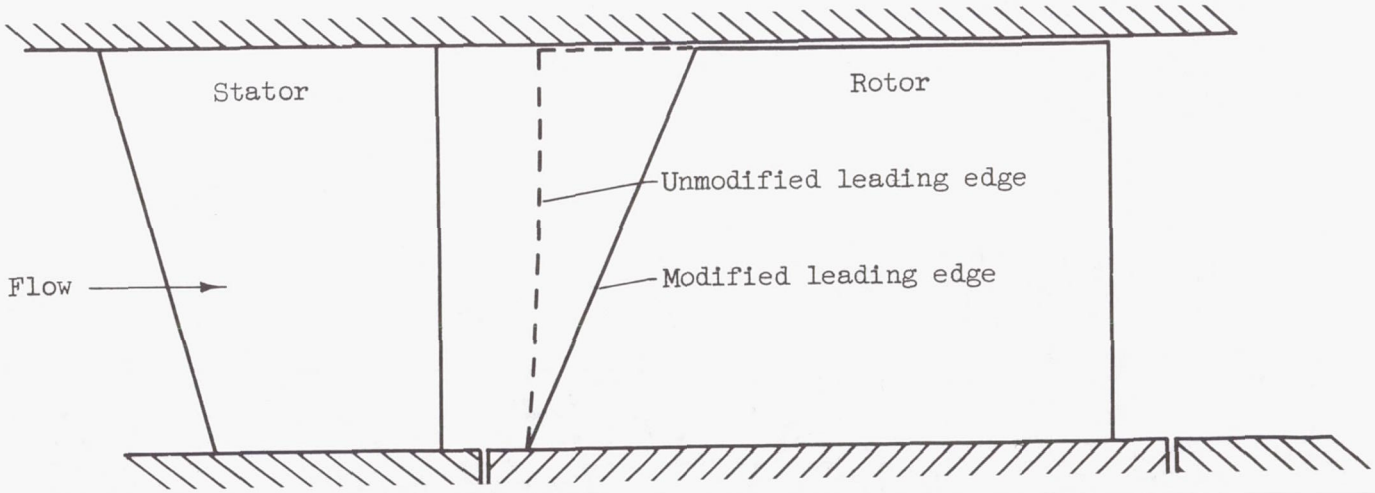


Figure 1. - Projection of unmodified and modified blades in radial-axial plane.

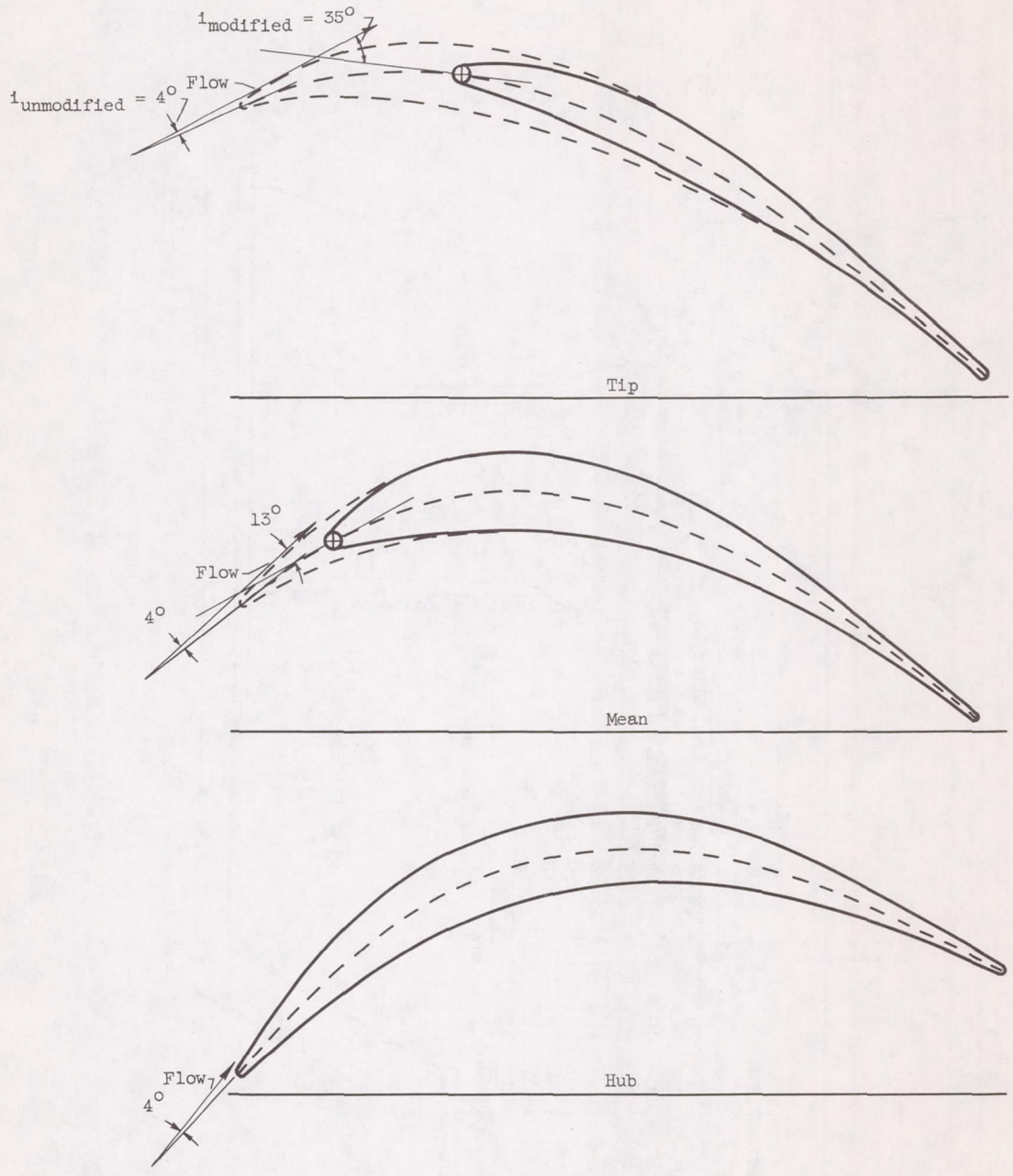


Figure 2. - Unmodified and modified blade profiles at hub, mean, and tip.

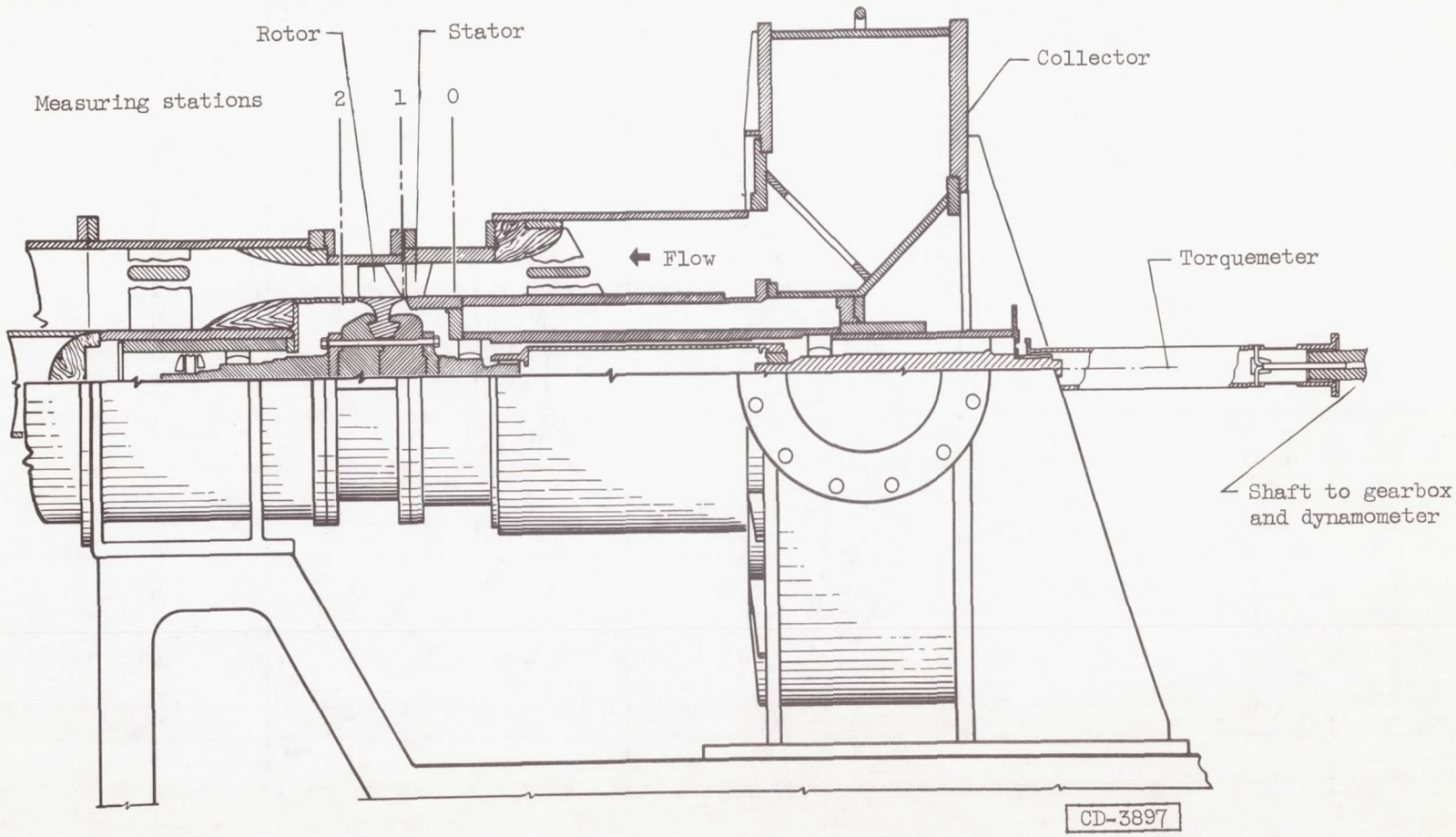


Figure 3. - Diagrammatic sketch of cold-air turbine test section.

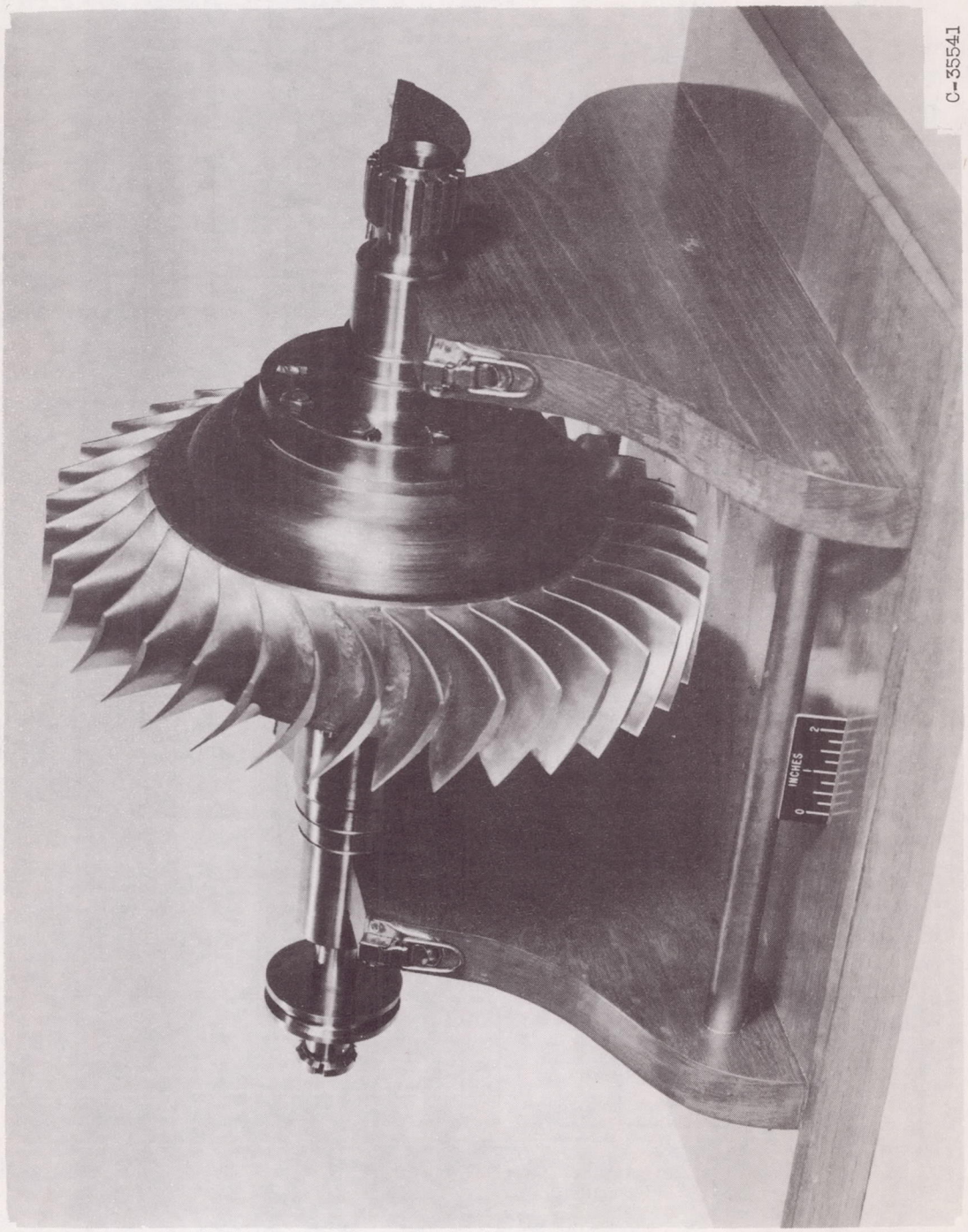
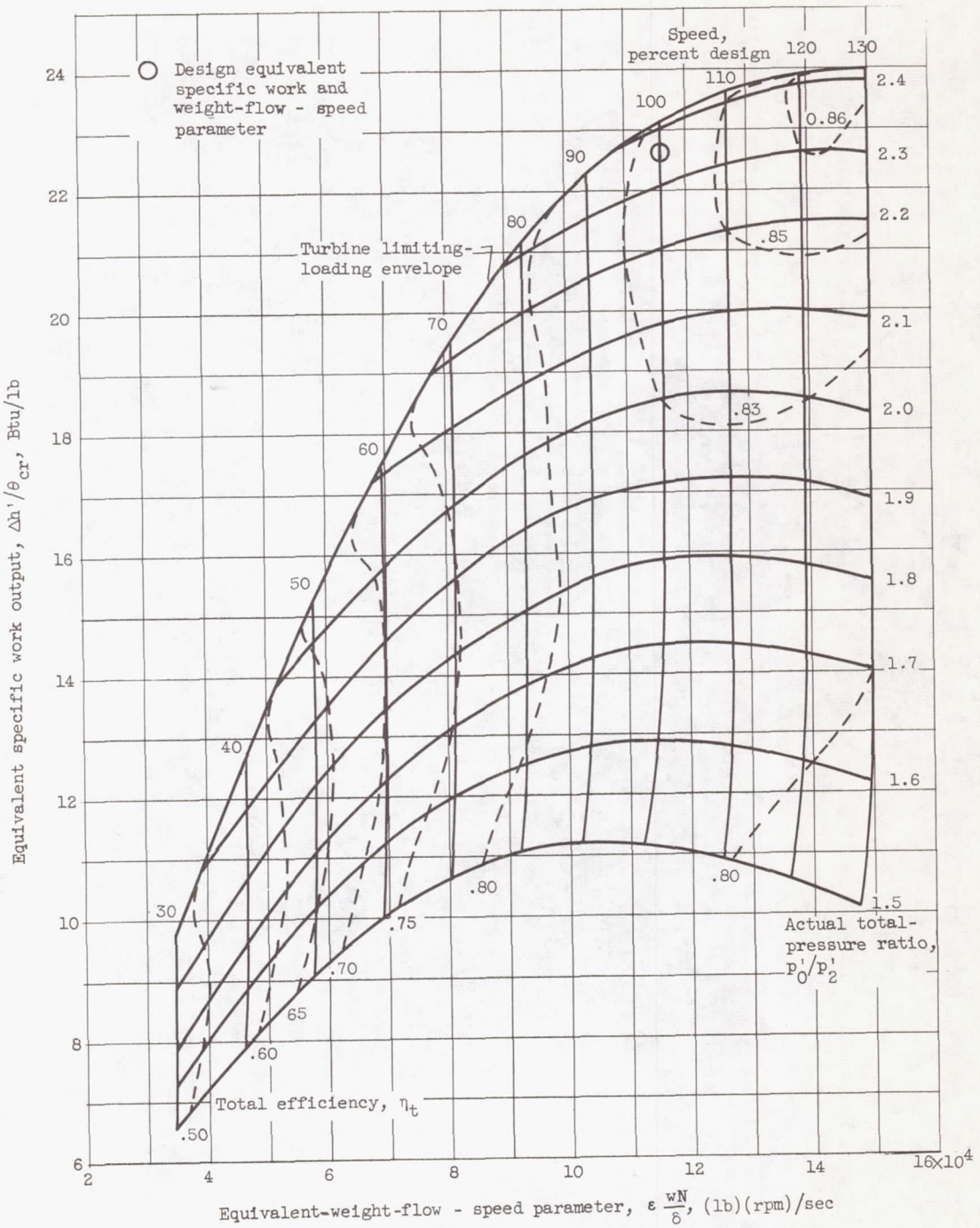
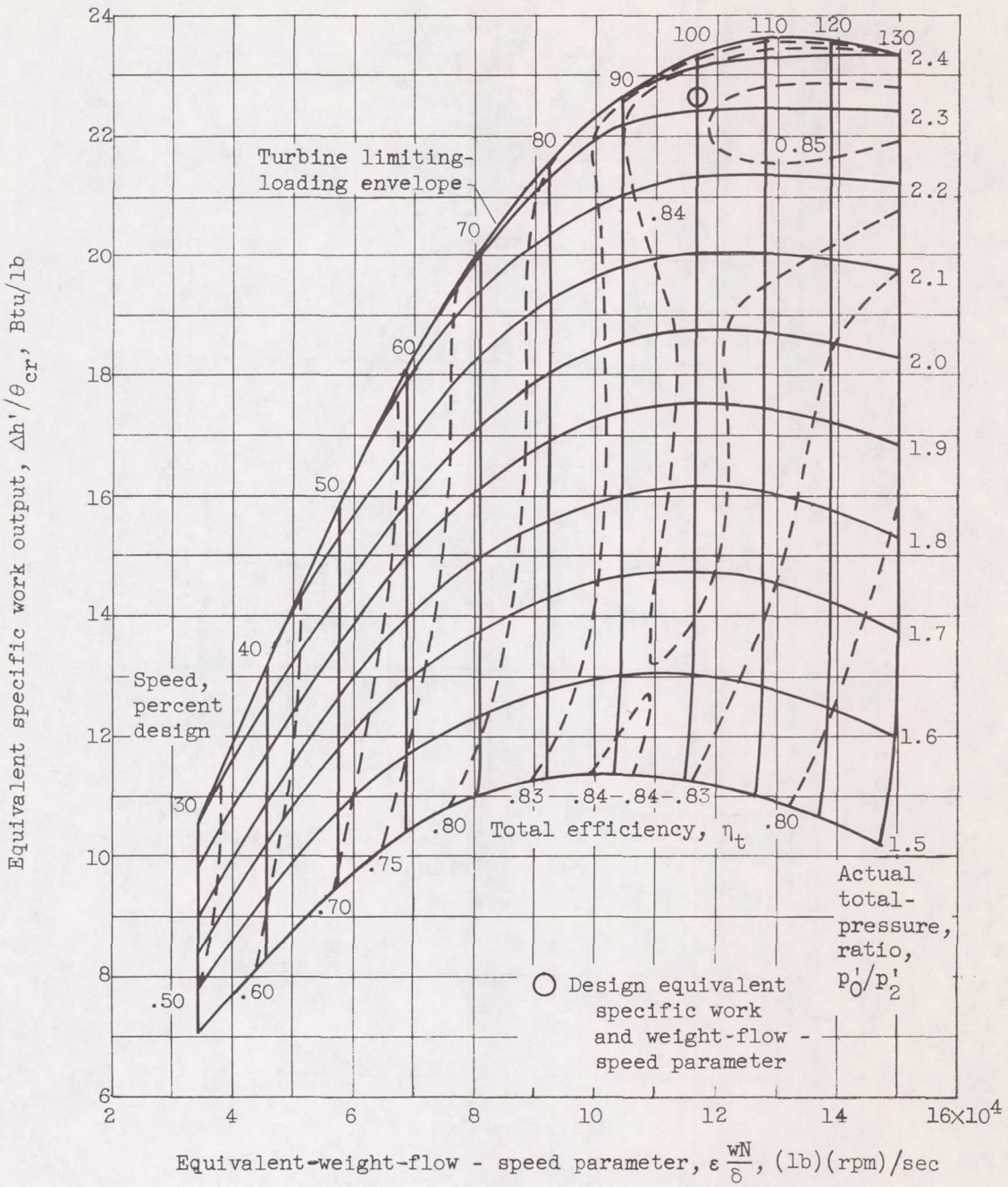


Figure 4. - Modified transonic turbine rotor.



(a) Modified rotor.

Figure 5. - Turbine performance maps.



(b) Unmodified rotor (ref. 3).

Figure 5. - Concluded. Turbine performance maps.

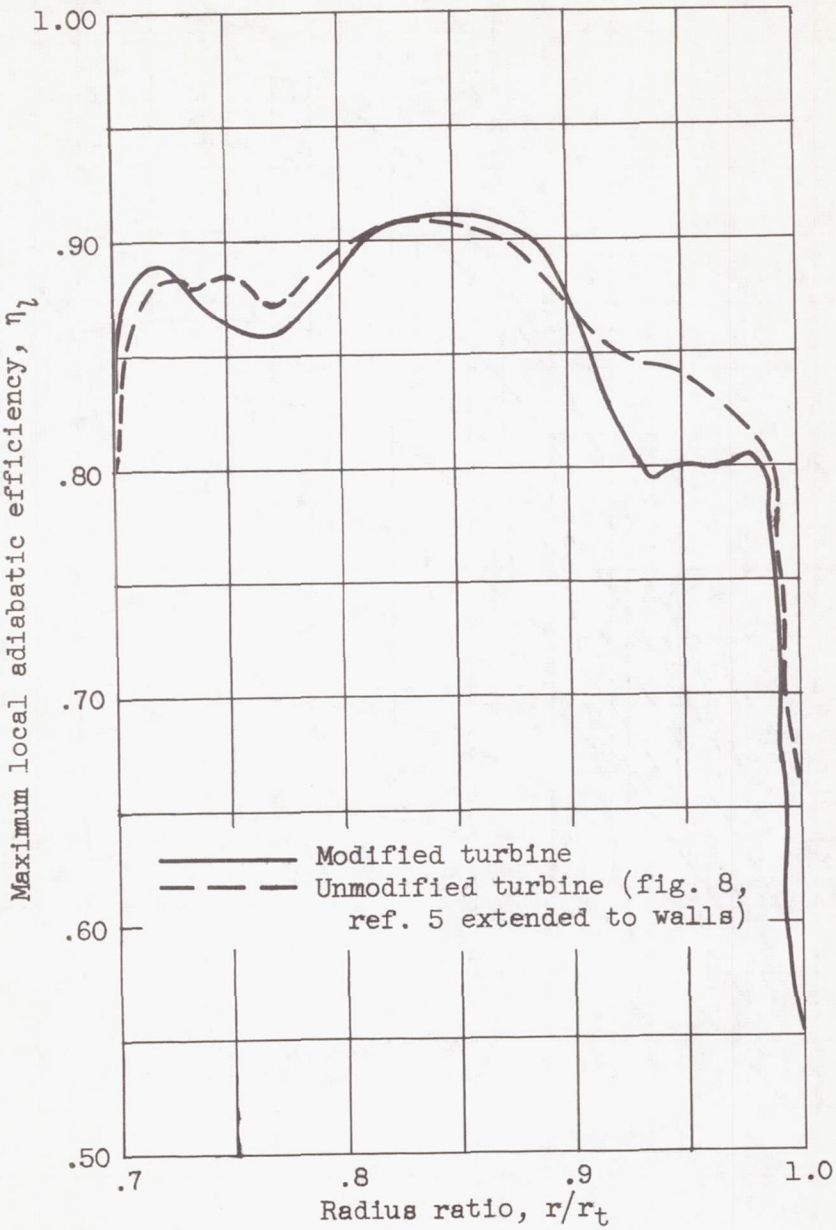


Figure 6. - Comparison of rotor-exit survey results obtained for unmodified and modified turbines at design point.